Physics 663

Adv Particle Physics

April 2014

Detectors

- Interaction of Charged Particles and Radiation with Matter
  - Ionization loss of charged particles
  - Coulomb scattering
  - Radiation loss by electrons
  - Radiation loss by muons
  - Absorption of γ -rays in Matter
- Detectors of Single Charged Particles
  - Proportional counters, Spark and streamer chambers, Drift chambers, Scintillation counters, Cerenkov counters, Solid-state counters,
  - Bubble chambers
- Shower Detectors and Calorimeters
  - Electromagnetic-shower detectors
  - Hadron-shower detectors

- References: Donald H. Perkins, Introduction to High Energy Physics, Fourth Edition

Interaction of Charged Particles and Radiation with Matter

- Ionization loss of charged particles
  - charged particles, passing through matter, lose energy primarily through scattering on the electrons in the medium
- Coulomb scattering
  - in scattering off the Coulomb field of the nucleus, the charged particle loses less energy, but suffers a large transverse deflection
- Radiation loss by electrons
  - in addition to losing energy through ionization (above), electrons lose significant energy through radiation

Ionization Loss of Charged Particles

- Charged particles, passing through matter, lose energy primarily through scattering on the electrons in the medium
- This process results in the Bethe-Bloch formula

$$\frac{dE}{dx} = \frac{4\pi N_0 z^2 \alpha^2}{m v^2} \frac{Z}{A} \left\{ \ln \left[\frac{2 m v^2}{I(1-\beta^2)} \right] - \beta^2 \right\}$$

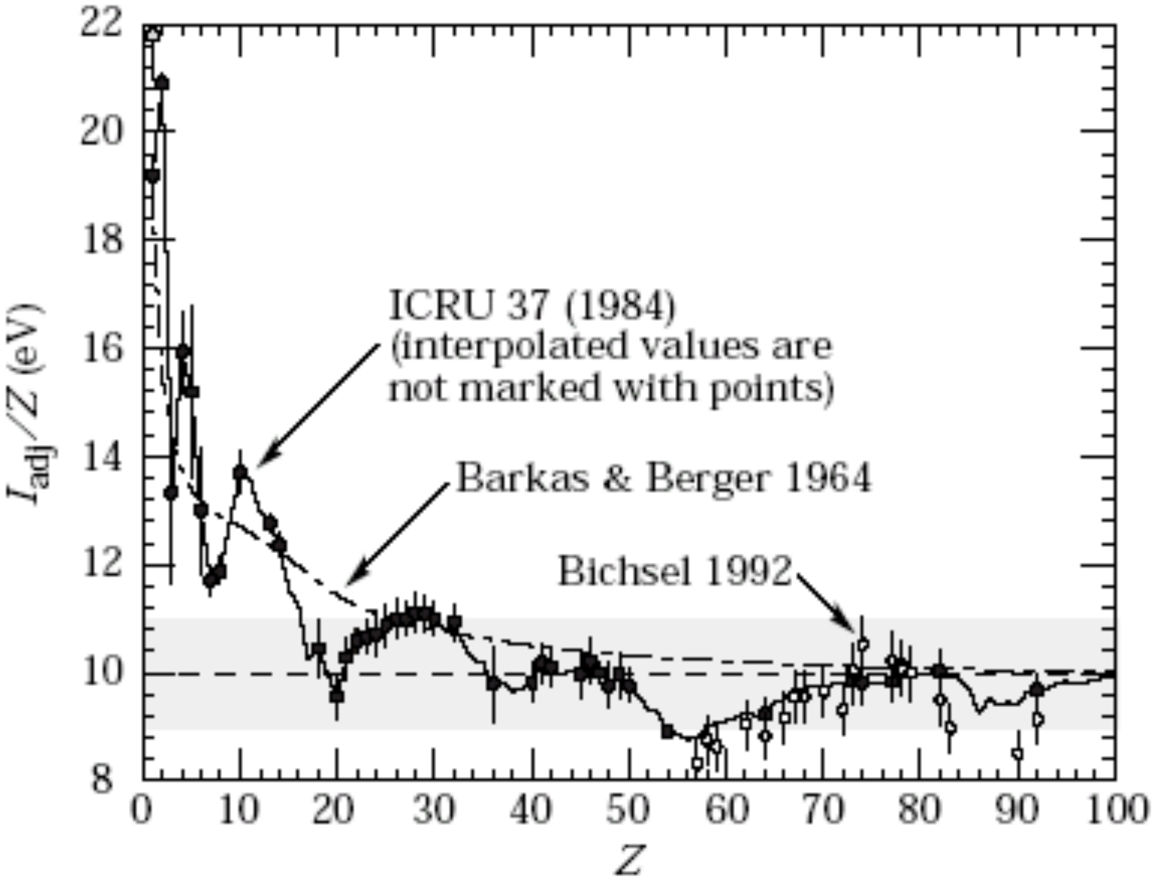
incident particle: ze, p, v, M
target Ze, A, m, I, x in g/cm^2

  - I ≈ 10 eV Z (see next page)
  - dE/dx
    - is independent of the mass M of the particle
    - varies as $1/v^2$ at non-relativistic velocities
    - increase logrithmically beyond minimum at $E \approx 3Mc^2$
    - depends weakly on the medium since $Z/A \approx 0.5$ for most media
    - ≈ 1 - 1.5 MeV cm^2 /g or 0.1 - 0.15 MeV m^2 /kg

Ionization Energy

Excitation energies (divided by Z). Those based on measurement are shown by points with error flags; the interpolated values are simply joined. The solid point is for liquid H_2; the open point at 19.2 is for H_2 gas. Also shown are curves based on two approximate formulae.

(from PDG)



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Ionization Loss of Charged Particles

- The Bethe-Bloch formula

$$\frac{dE}{dx} = \frac{4\pi N_0 z^2 \alpha^2}{mv^2} \frac{Z}{A} \left\{ \ln\left[\frac{2mv^2}{I(1-\beta^2)} \right] - \beta^2 \right\}$$

emerges from Rutherford scattering (moving electron, stationary target atom)

$$\frac{d\sigma}{dq^2} = \frac{4\pi\alpha^2 z^2}{v^2 q^4}$$

- For a massive nucleus, these is no energy transfer
- In the rest frame of the electron, the electron acquires a recoil energy T, where $q^2 = 2mT$

$$\frac{d\sigma}{dT} = \frac{2\pi\alpha^2 z^2}{mv^2} \frac{1}{T^2}$$

Ionization Loss of Charged Particles

- Now, consider the number of such scatters in the energy range T → T + dT, in traversing dx, for a medium of atomic number Z

$$dN = \frac{2\pi N_0 \alpha^2 z^2}{mv^2} \frac{Z}{A} \frac{dT}{T^2} dx$$

- So ionization energy loss is

$$\frac{dE}{dx} = \int T \frac{dN}{dx} = \frac{2\pi N_0 \alpha^2 z^2}{mv^2} \frac{Z}{A} \ln \frac{T_{\max}}{T_{\min}}$$

  - the maximum energy loss is

$$T_{\max} = \frac{2mv^2 E^2}{M^2 + m^2 + 2mE} \approx \frac{2mv^2}{1-\beta^2} \quad \text{at low energy}$$

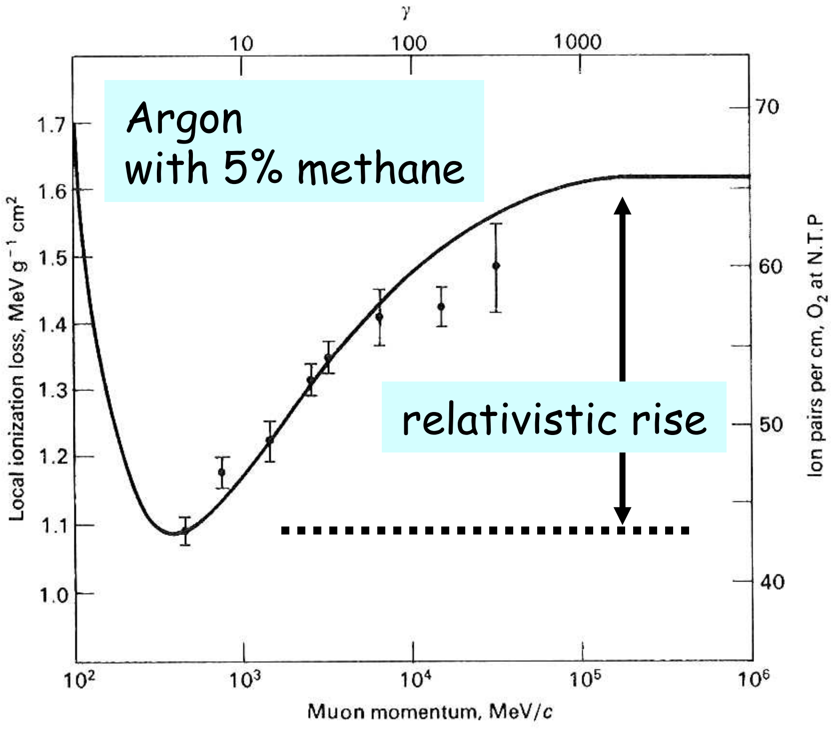
  - and the minimum is I, the mean ionization potential

Ionization Loss of Charged Particles

$$\frac{dE}{dx} = \int T \frac{dN}{dx} = \frac{2\pi N_0 \alpha^2 z^2}{m v^2} \frac{Z}{A} \ln \frac{T_{\max}}{T_{\min}}$$

- Insert T_{max} and T_{min}, and add a factor of 2 which accounts for effects such as atomic excitation, and Bethe-Bloch equation is found (after proper relativistic treatment

$$\frac{dE}{dx} = \frac{4\pi N_0 z^2 \alpha^2}{m v^2} \frac{Z}{A} \left\{ \ln \left[\frac{2 m v^2}{I(1-\beta^2)} \right] - \beta^2 \right\}$$

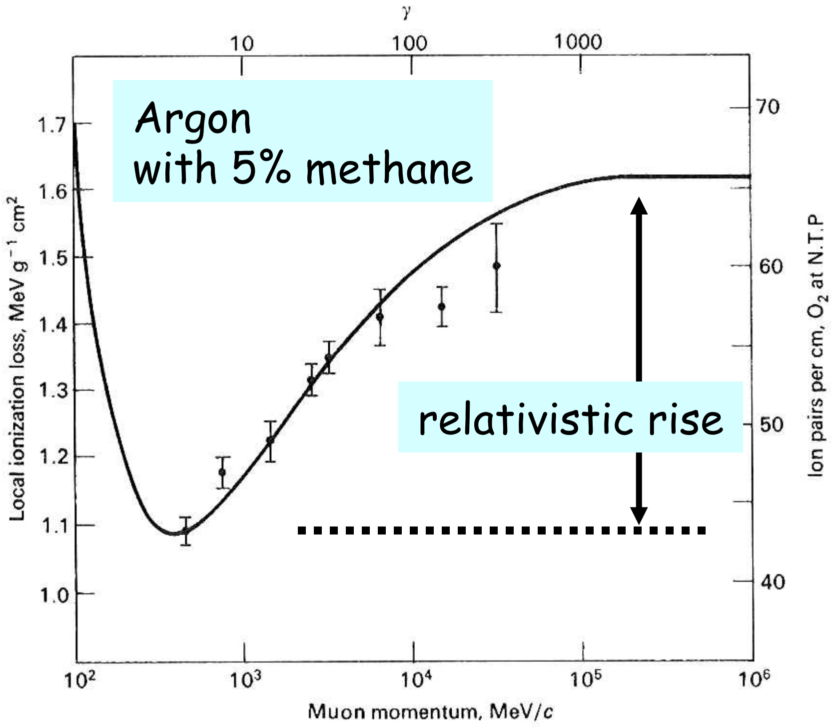


Argon
with 5% methane

relativistic rise

Ionization Loss of Charged Particles

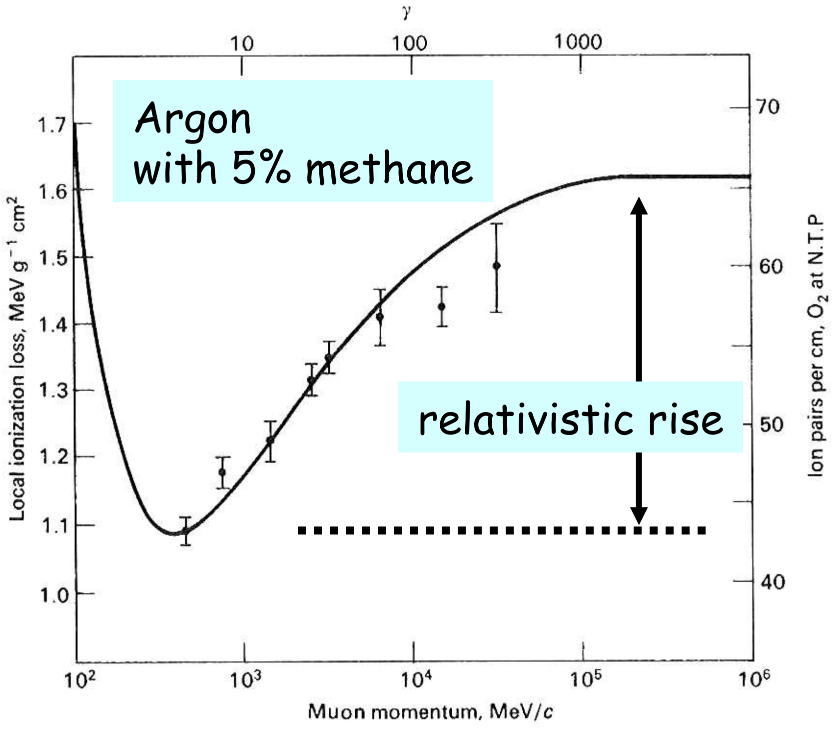
- Relativistic rise
  - transverse electric field rises with γ, resulting from more distant collisions
  - polarization effects cut off rise
  - polarization effects are stronger in solids than gas
    - gas: rise ~ 1.5
    - solid: rise ~ 1.1


Argon
with 5% methane

relativistic rise

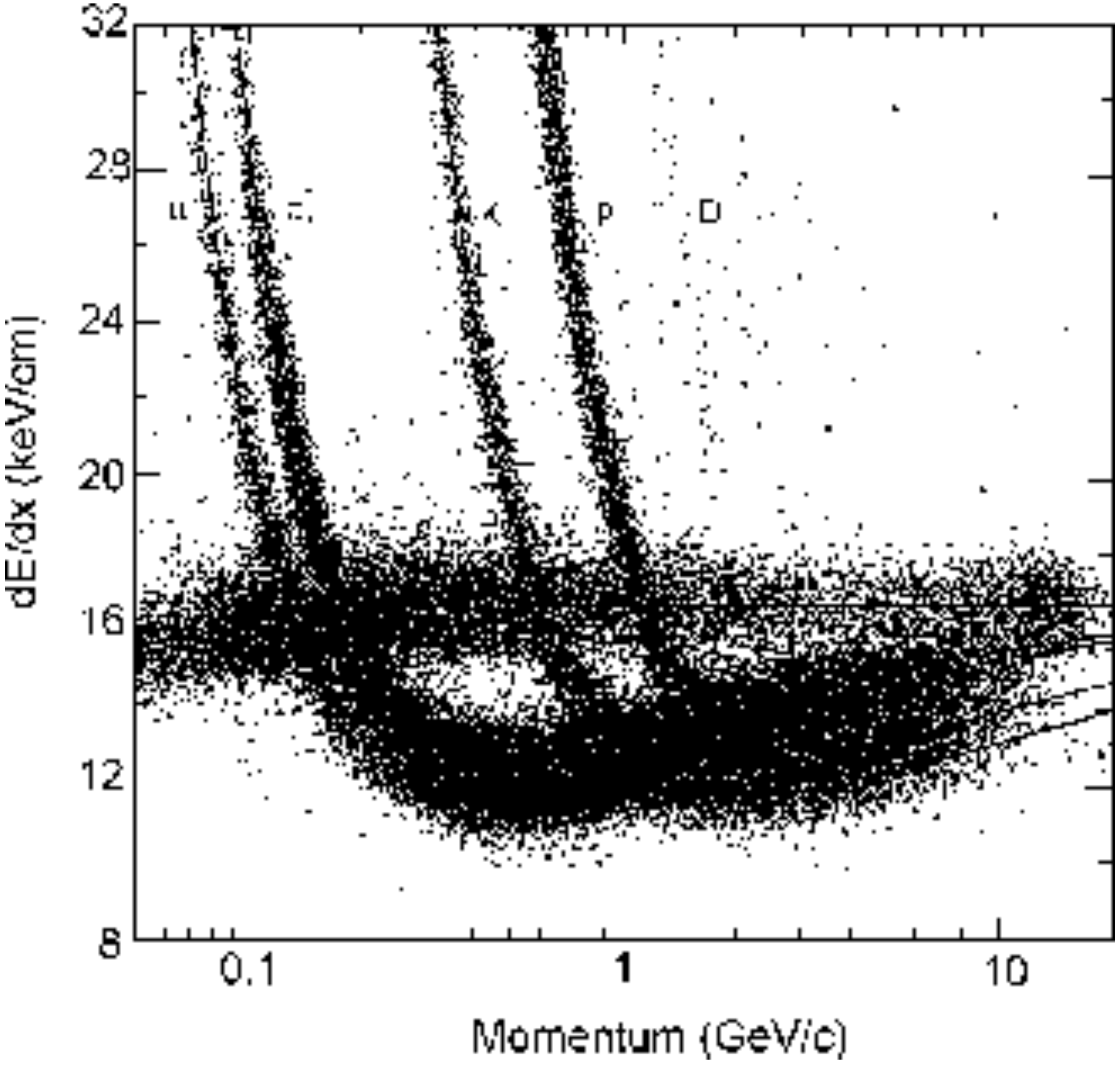
Ionization Loss of Charged Particles

- Ion pairs
  - Landau distribution
    - large fluctuations in energy loss
    - higher energy electrons (δ rays)
  - Number of pairs depends on energy required to produce pair in medium
    - helium: 40 eV
    - argon: 26 eV
    - semi-cond: 3 eV



Ionization Loss of Charged Particles

- Measured ionization energy loss of electrons, muons, pions, kaons, protons and deuterons in the PEP4/9-TPC

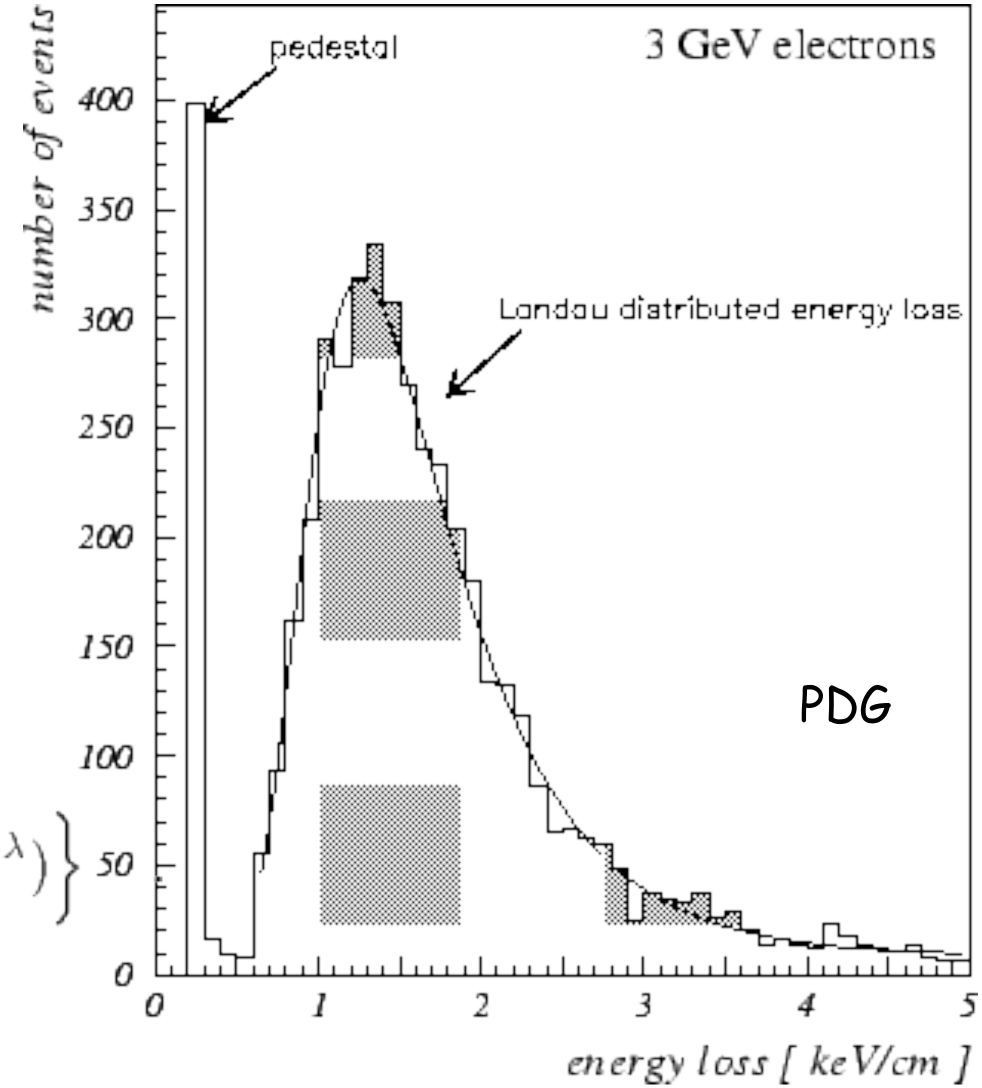


Landau Distribution

- The Bethe-Bloch formula describes the average energy loss of charged particles. The fluctuation of the energy loss around the mean is described by an asymmetric distribution, the Landau distribution. An approximation is

$$\Omega(\lambda) = \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{1}{2}(\lambda + e^{-\lambda})\right\}$$

- The high energy tail can complicate mass determination.



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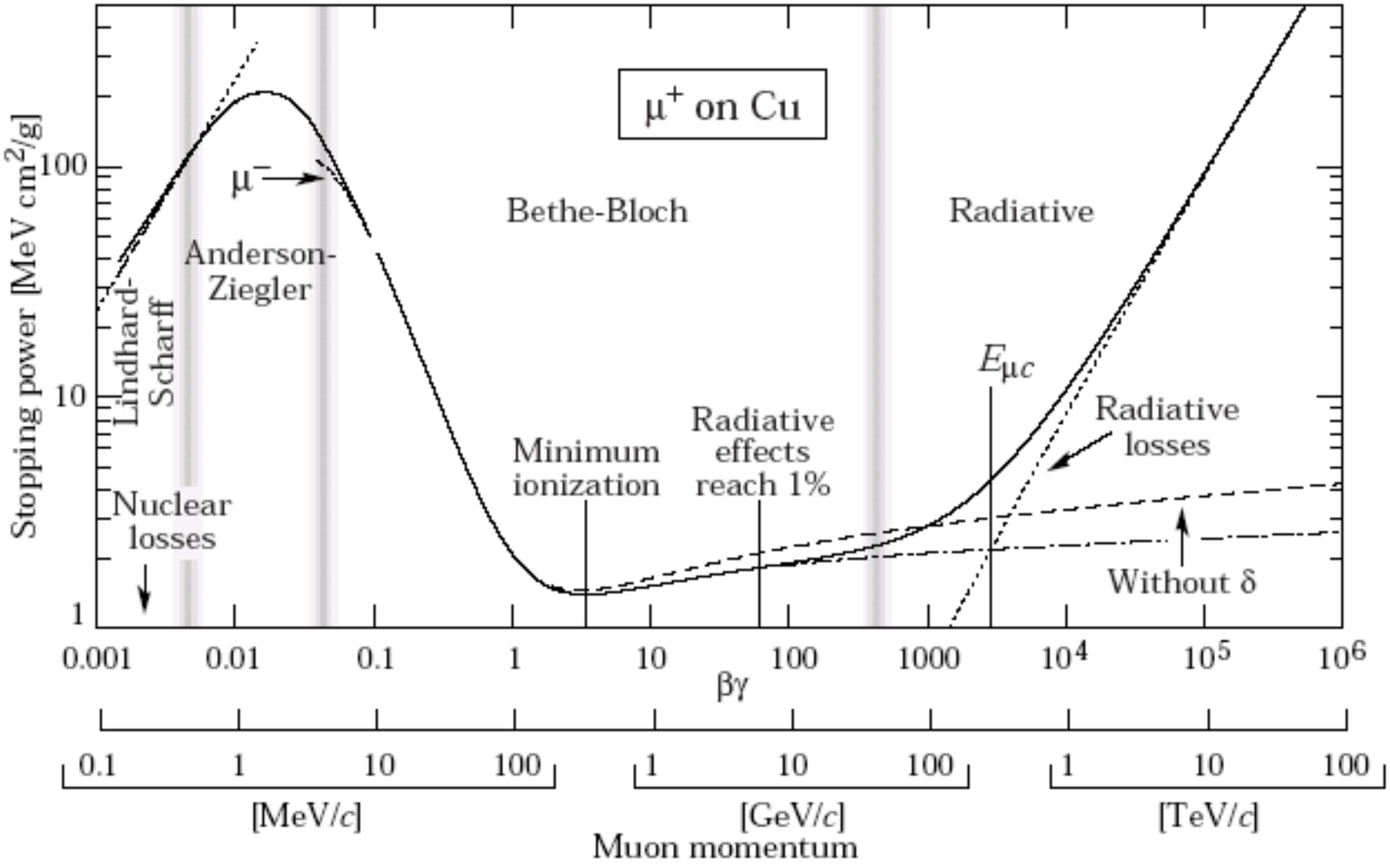
Bethe-Bloch Equation with Density Corrections

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\mathrm{max}}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$



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Coulomb scattering

- In scattering off the Coulomb field of the nucleus, the charged particle loses less energy than in scattering from the electrons, since the energy loss formula ~ 1/m

$$\frac{dE}{dx} = \frac{4\pi N_0 z^2 \alpha^2}{mv^2} \frac{Z}{A} \left\{ \ln\left[\frac{2mv^2}{I(1-\beta^2)} \right] - \beta^2 \right\}$$

- but suffers a larger transverse deflection in scattering from the nucleus than the electrons

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{1}{4} \left(\frac{Zz\alpha}{pv} \right)^2 \frac{1}{\sin^4(\theta/2)}$$

incident particle: ze, p, v

target Ze

Coulomb scattering

- In passing through a layer of material, many scatters occur, resulting in a net angle of multiple scattering which approximates a Gaussian distribution

$$P(\phi)d\phi = \frac{2\phi}{\langle\phi^2\rangle}\exp\left(\frac{-\phi^2}{\langle\phi^2\rangle}\right)d\phi$$

- The rms deflection in distance t depends on the medium

$$\phi_{\text{rms}} = \langle\phi^2\rangle^{1/2} = \frac{zE_s}{pv}\sqrt{\frac{t}{X_0}}$$

$$E_s = \sqrt{4\pi \times 137}\quad mc^2 = 21\text{ MeV}$$

$$\frac{1}{X_0} = 4Z^2\left(\frac{N_0}{A}\right)\alpha^3\left(\frac{\hbar c}{mc^2}\right)^2\ln\left(\frac{183}{Z^{1/3}}\right)$$

- X_0 is called the *radiation length*

Coulomb scattering

$$\phi_{\mathrm{rms}} = \langle \phi^2 \rangle^{1/2} = \frac{zE_s}{pv}\sqrt{\frac{t}{X_0}} \quad ; \quad E_s = 21 \text{ MeV}$$

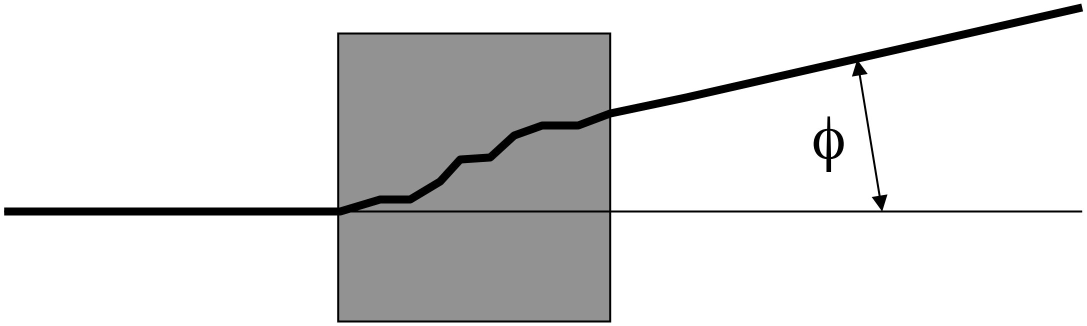
Element	Z	E_c, MeV	X_0, g cm^{-2}
hydrogen	1	340	63.1
helium	2	220	94.3
carbon	6	103	42.7
aluminium	11	47	24.0
iron	26	24	13.8
lead	82	6.9	6.4

- Measured along one axis (say the x axis), the rms angular deflection is 1/√2 the above expression

Coulomb scattering

$$\phi_{\rm rms} = \langle \phi^2 \rangle^{1/2} = \frac{zE_s}{pv}\sqrt{\frac{t}{X_0}} \quad ; \quad E_s = 21 \text{ MeV}$$

- Multiple coulomb scattering limits the precision of determining the direction of a particle



Coulomb scattering

$$\phi_{\text{rms}} = \langle \phi^2 \rangle^{1/2} = \frac{zE_s}{pv}\sqrt{\frac{t}{X_0}}$$; E_s = 21 MeV

- Consider the measurement of the curvature of a particle's path in a magnetic field
- Radius of curvature of the track (ρ) is given by expression

$$p\,c = B\,e\,\rho$$

$$p(\text{GeV}/c) = 0.3\ B(\text{Tesla})\ \rho\ (\text{meters})$$

  - or in terms of deflection in distance s: $\phi_{mag} = s/\rho = 0.3\ s\ B\ /\ p$
- At the same time, the direction of the track is altered by mulitple Coulomb scattering

$$\phi_{\text{scat}} = \frac{0.021}{\sqrt{2}}\frac{1}{p\beta c}\sqrt{\frac{s}{X_0}}$$

so $$\frac{\phi_{\text{scat}}}{\phi_{\text{mag}}} = \frac{0.05}{B\beta\sqrt{X_0 s}}$$

Iron, X_0= 0.02 m

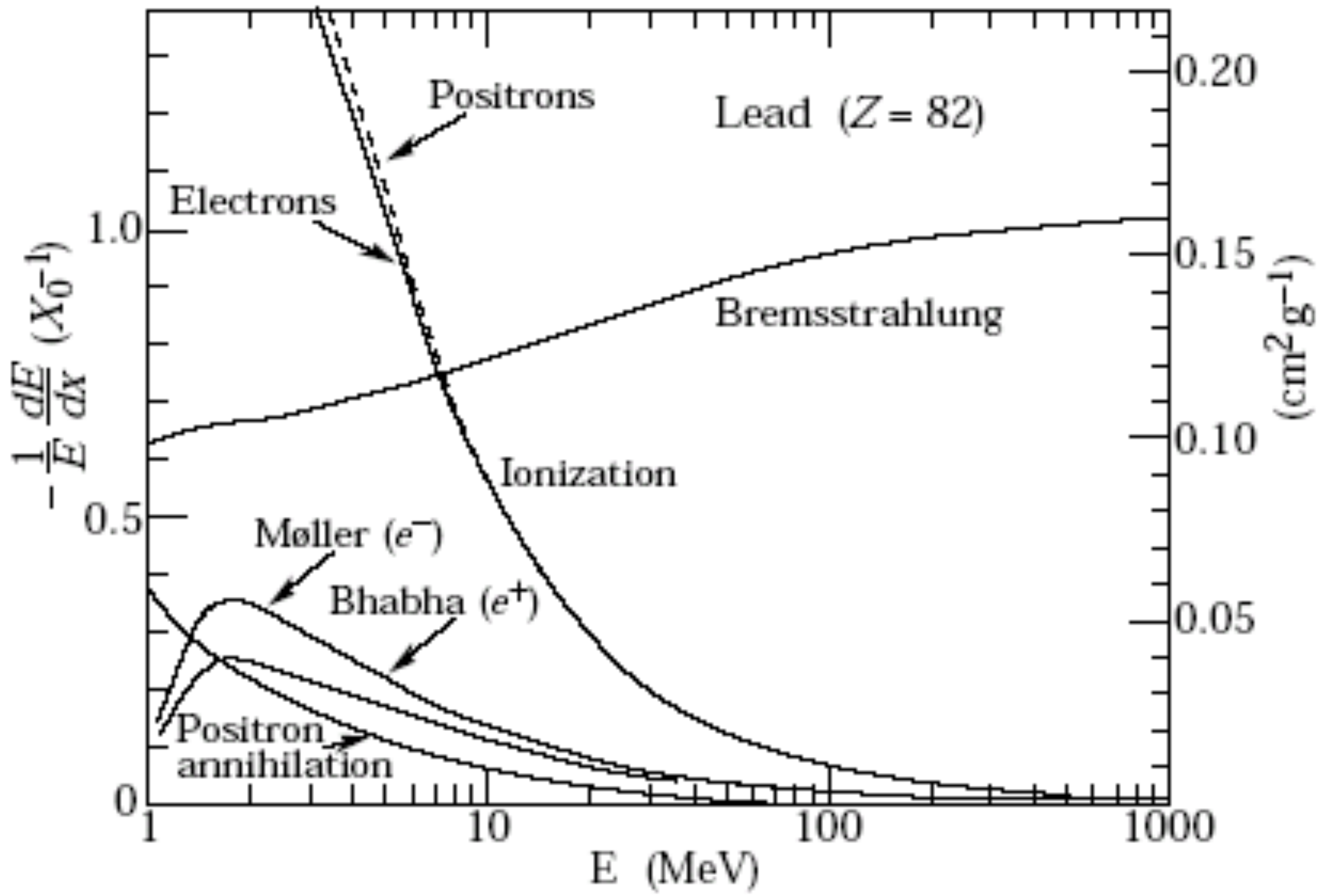
s	ϕ_{scat}/ϕ_{mag}
1 m	0.25
6 m	0.10

Radiation loss by electrons

- In addition to losing energy through ionization (above), electrons lose significant energy through radiation
- This loss results principally through collisions with the nucleus, and therefore is parametrized by the same length as Coulomb scattering, the radiation length (X_0)
- In interacting with the electric field of a nucleus, an electron will radiate photons, in a process known as bremsstrahlung ("braking radiation")
  - photon energy spectrum dE' / E'
  - total loss in distance dx $$\left(\frac{dE}{dx}\right)_{\text{rad}} = -\frac{E}{X_0}$$
  - integration easily shows the energy surviving after a thickness x

$$\langle E \rangle = E_0 \exp\left(-\frac{x}{X_0}\right)$$

Radiation loss by electrons



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Radiation loss by electrons

- Critical Energy (E_c)
  - so the energy loss by electron has two components

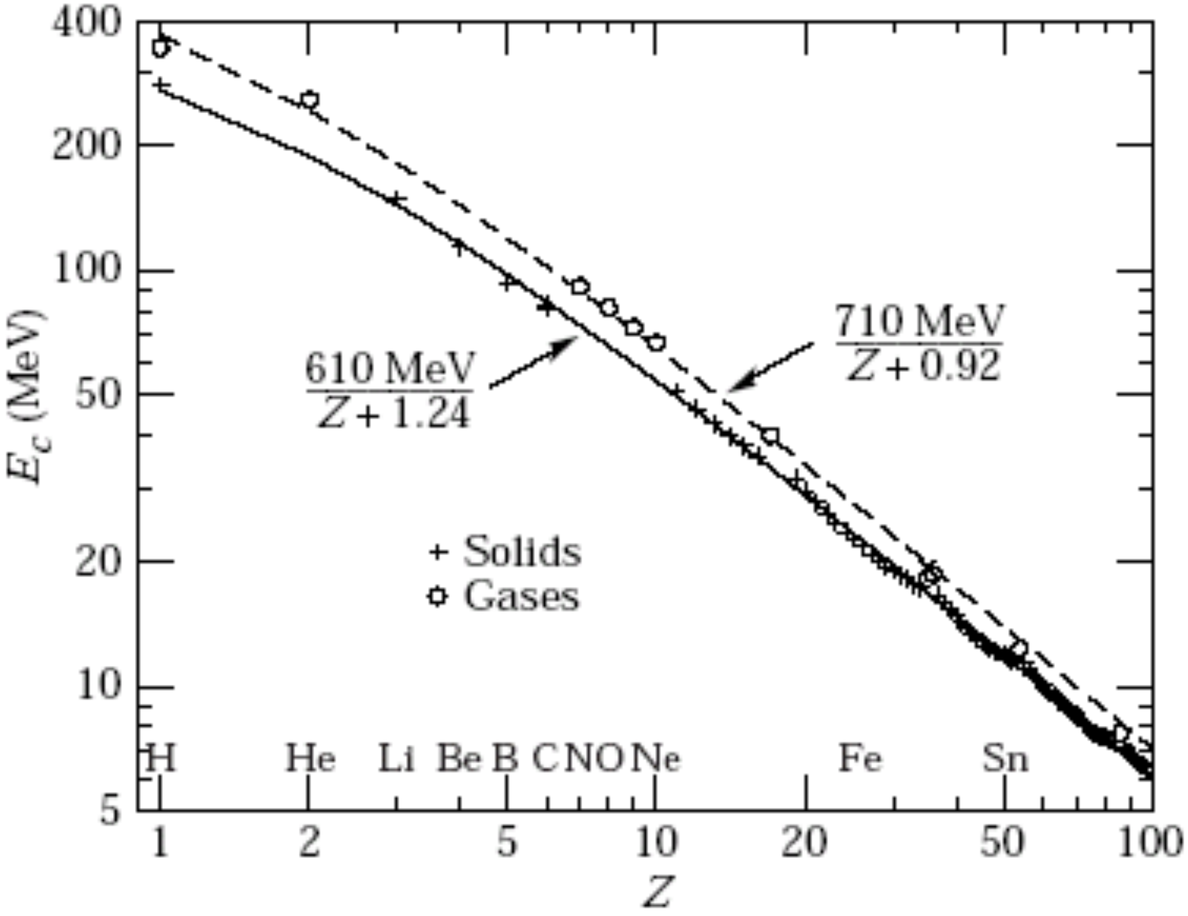
$$\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_{\text{ion}} + \left(\frac{dE}{dx}\right)_{\text{rad}}$$

  - the ionization loss for high energy electrons is approximately constant
  - however, the energy loss by radiation is proportional to E
  - the critical energy (E_c) is defined as that energy where these two mechanisms are equal
  - for Z > 5

$$E_c \simeq \frac{600}{Z}\ \text{MeV}$$

Element	Z	E_c, MeV
hydrogen	1	340
helium	2	220
carbon	6	103
aluminium	11	47
iron	26	24
lead	82	6.9

Radiation loss by electrons



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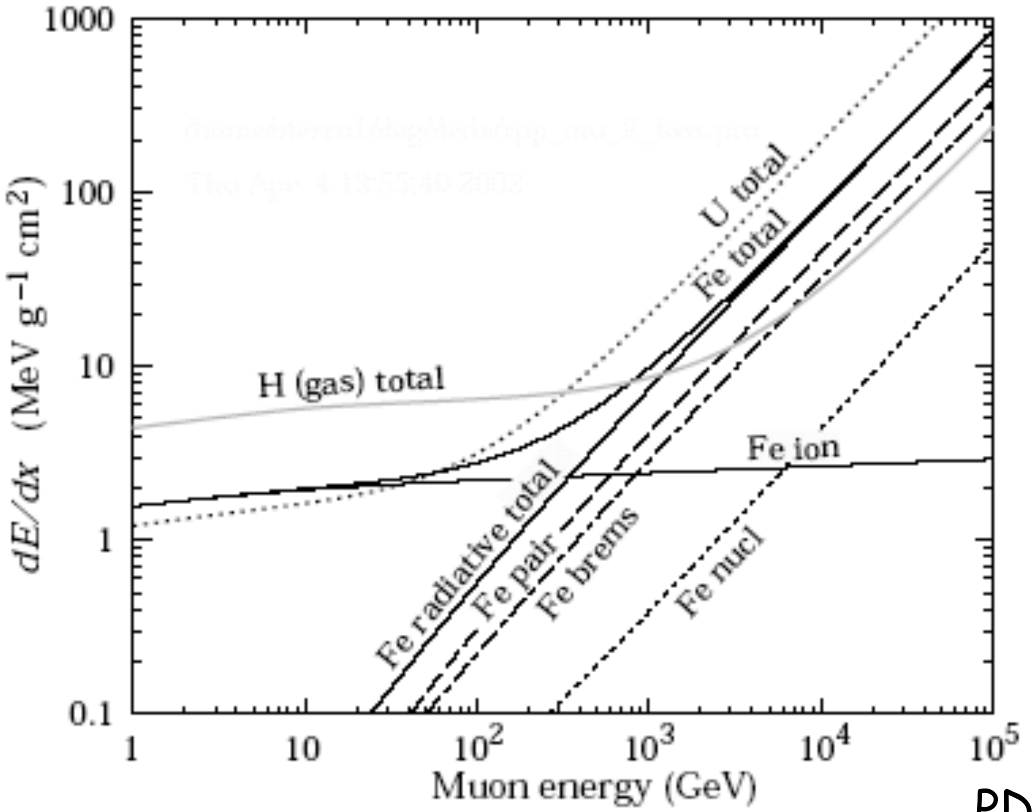
Radiation loss by muons

- For muons with energies above a few hundred GeV, bremsstrahlung and direct *e+e*⁻ production dominate ionization losses especially in heavy materials.



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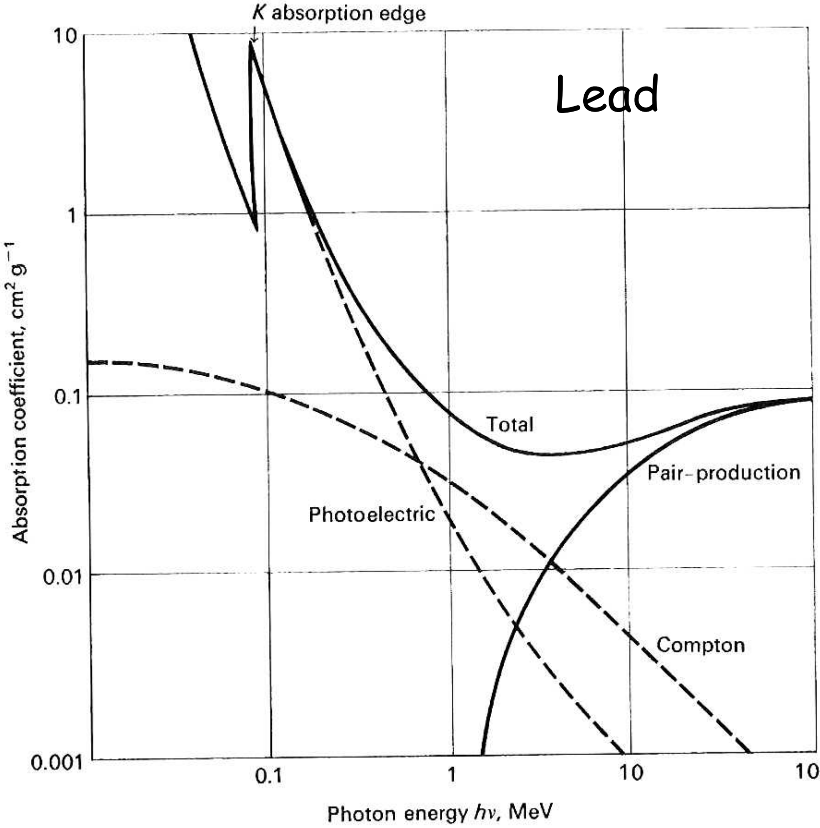
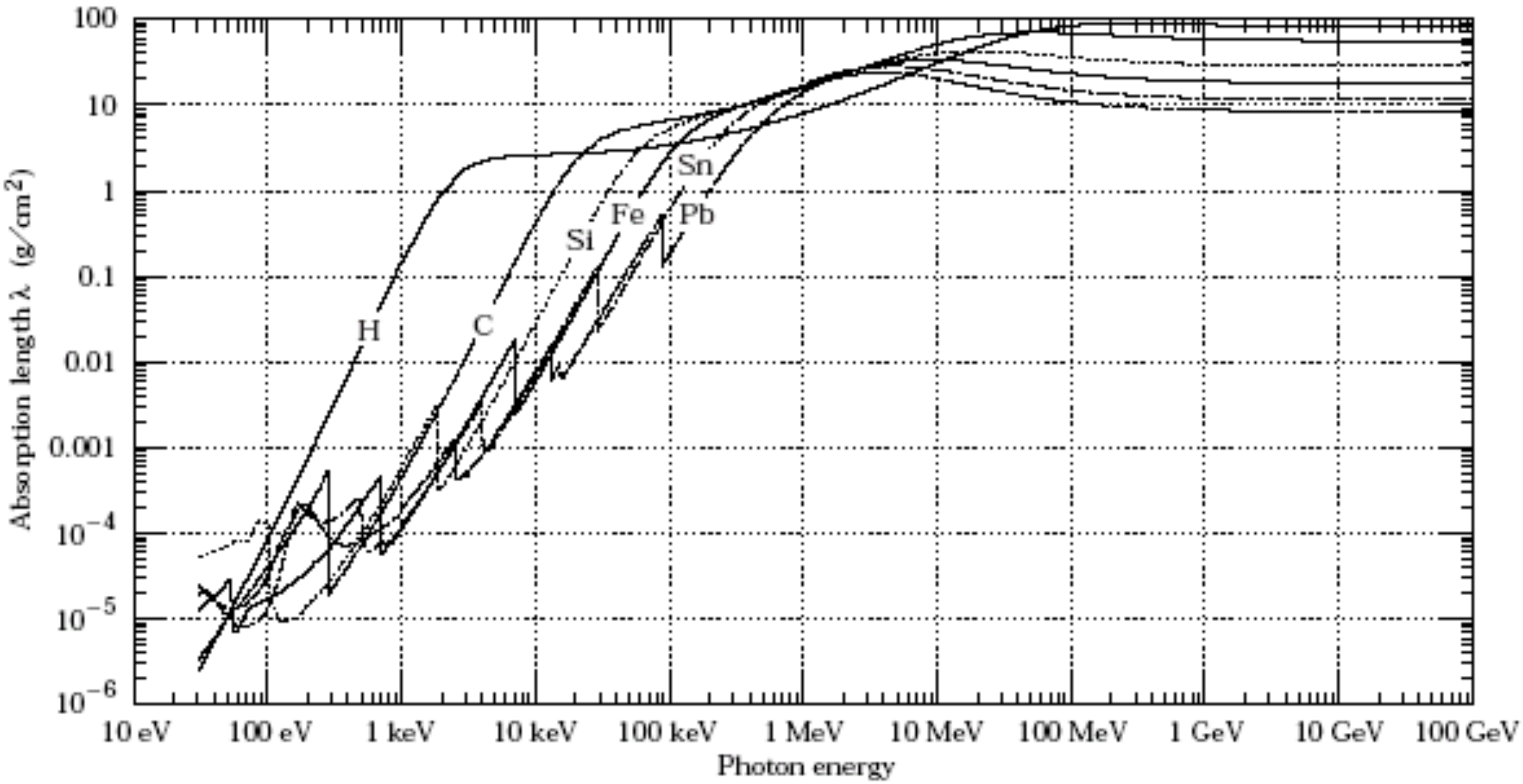
Absorption of γ -rays in Matter

- γ -rays are attenuated through three types of processes:
  - Photoelectric effect
    $\sigma \sim 1/E^3$
  - Compton scattering
    $\sigma \sim 1/E$
  - Pair production
    $\sigma \sim$ constant
    above threshold



- Above ~10 MeV,
  pair production dominant,
  and attenutaion energy
  independent

Absorption of γ -rays in Matter



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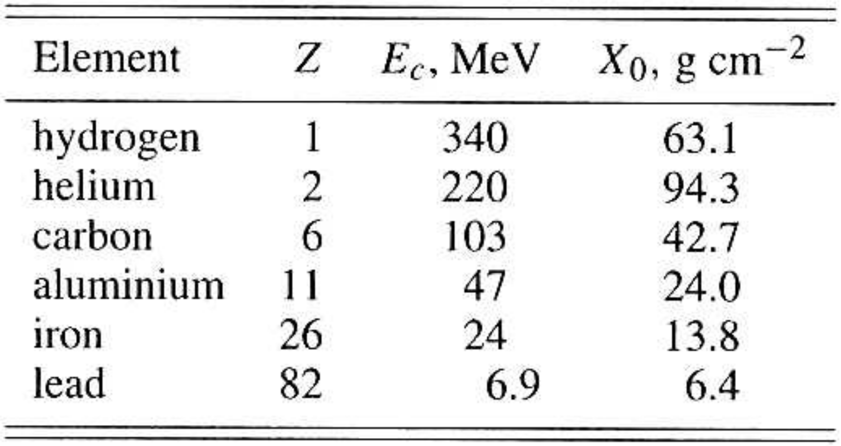
Absorption of γ -rays in Matter

- Again, since the process of pair production is closely related to electron beamsstrahlung (interactions with the electron field of the nucleus) both are described by the radiation length

$$I = I_0 \exp\left(-\frac{7x}{9X_0}\right)$$



Element	Z	E_c, MeV	X_0, g cm^{-2}
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helium	2	220	94.3
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aluminium	11	47	24.0
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lead	82	6.9	6.4

- Absorption length:

$9/7\ X_0$

Other important processes

- Interactions
  - charged hadrons
    - p, π, K, etc.
  - neutral hadrons
    - neutrons
    - K^0_L
  - nuclear breakup
- Decays in flight
  - eg. $\pi \rightarrow \mu\ \nu_\mu$

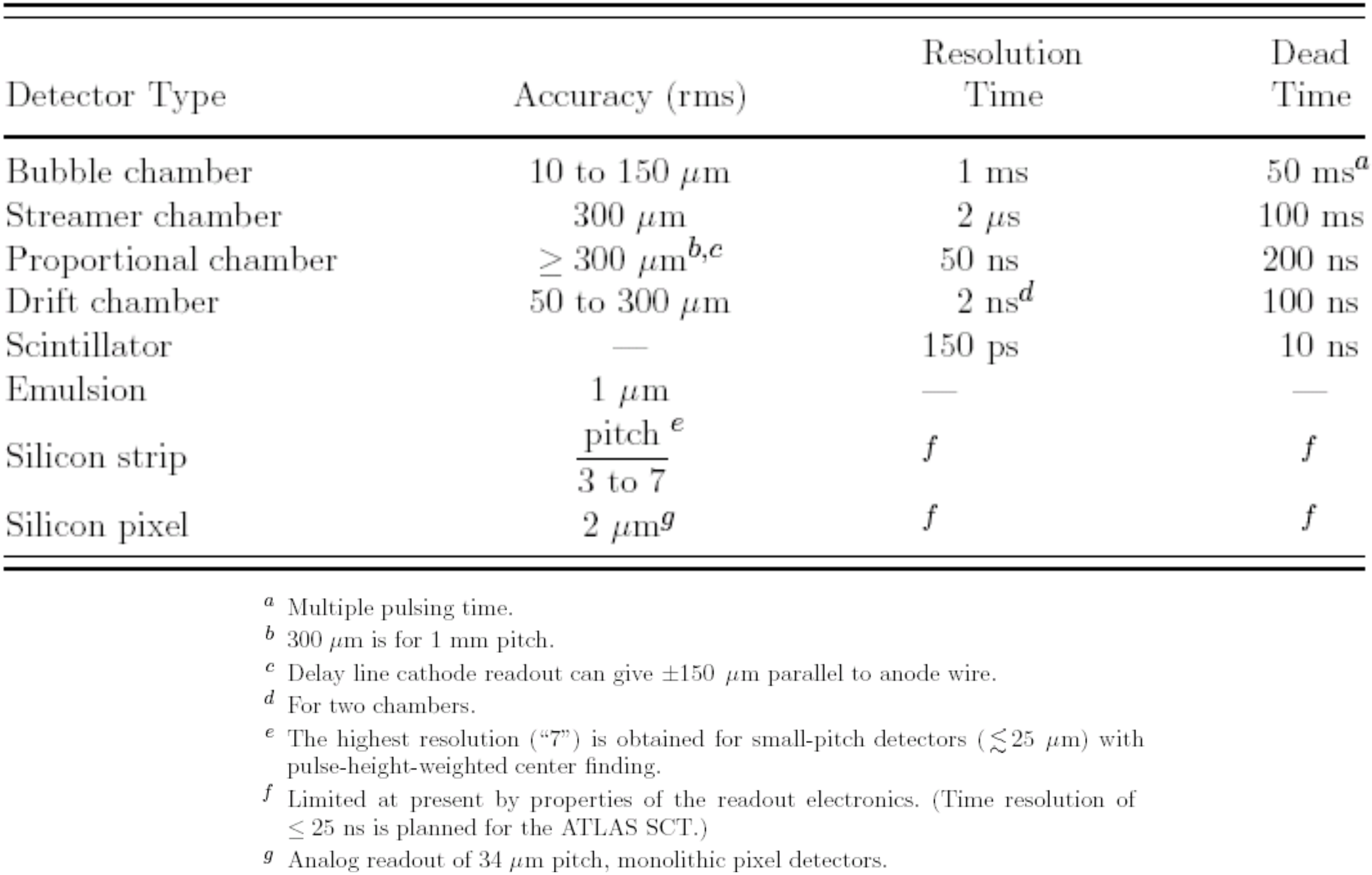
Properties of Materials

Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T $\{g/cm^2\}$	Nuclear [a] interaction length λ_I $\{g/cm^2\}$	$dE/dx\|_{min}$ [b] $\left\{\frac{MeV}{g/cm^2}\right\}$	Radiation length [c] X_0 $\{g/cm^2\}$	$\{cm\}$	Density $\{g/cm^3\}$ ($\{g/\ell\}$ for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times 10^6$ for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—

Properties of Materials

Material	Z	A	$\langle Z/A \rangle$	Nuclear[a] collision length λ_T $\{g/cm^2\}$	Nuclear[a] interaction length λ_I $\{g/cm^2\}$	$dE/dx\|_{min}$[b] $\left\{\frac{MeV}{g/cm^2}\right\}$	Radiation length[c] X_0 $\{g/cm^2\}$	$\{cm\}$	Density $\{g/cm^3\}$ ($\{g/\ell\}$ for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times10^6$ for gas)
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H_2O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33
CO_2 gas			0.49989	62.4	89.7	(1.819)	36.2	[18310]	[1.977]		[410]
CO_2 solid (dry ice)			0.49989	62.4	89.7	1.787	36.2	23.2	1.563	sublimes	—
Shielding concrete [f]			0.50274	67.4	99.9	1.711	26.7	10.7	2.5		—
SiO_2 (fused quartz)			0.49926	66.5	97.4	1.699	27.05	12.3	2.20 [g]		1.458
Dimethyl ether, $(CH_3)_2O$			0.54778	59.4	82.9	—	38.89	—	—	248.7	—
Methane, CH_4			0.62333	54.8	73.4	(2.417)	46.22	[64850]	0.4224[0.717]	111.7	[444]
Ethane, C_2H_6			0.59861	55.8	75.7	(2.304)	45.47	[34035]	0.509(1.356) [h]	184.5	(1.038) [h]
Propane, C_3H_8			0.58962	56.2	76.5	(2.262)	45.20	—	(1.879)	231.1	—
Isobutane, $(CH_3)_2CHCH_3$			0.58496	56.4	77.0	(2.239)	45.07	[16930]	[2.67]	261.42	[1900]
Octane, liquid, $CH_3(CH_2)_6CH_3$			0.57778	56.7	77.7	2.123	44.86	63.8	0.703	398.8	1.397
Paraffin wax, $CH_3(CH_2)_{n\approx23}CH_3$			0.57275	56.9	78.2	2.087	44.71	48.1	0.93		—
Nylon, type 6 [i]			0.54790	58.5	81.5	1.974	41.84	36.7	1.14		—
Polycarbonate (Lexan) [j]			0.52697	59.5	83.9	1.886	41.46	34.6	1.20		—
Polyethylene terephthlate (Mylar) [k]			0.52037	60.2	85.7	1.848	39.95	28.7	1.39		—
Polyethylene [l]			0.57034	57.0	78.4	2.076	44.64	≈47.9	0.92–0.95		—
Polyimide film (Kapton) [m]			0.51264	60.3	85.8	1.820	40.56	28.6	1.42		—
Lucite, Plexiglas [n]			0.53937	59.3	83.0	1.929	40.49	≈34.4	1.16–1.20		≈1.49
Polystyrene, scintillator [o]			0.53768	58.5	81.9	1.936	43.72	42.4	1.032		1.581
Polytetrafluoroethylene (Teflon) [p]			0.47992	64.2	93.0	1.671	34.84	15.8	2.20		—
Polyvinyltolulene, scintillator [q]			0.54155	58.3	81.5	1.956	43.83	42.5	1.032		—
Aluminum oxide (Al_2O_3)			0.49038	67.0	98.9	1.647	19.27	4.85	3.97		1.761
Barium fluoride (BaF_2)			0.42207	92.0	145	1.303	9.91	2.05	4.89		1.56
Bismuth germanate (BGO) [r]			0.42065	98.2	157	1.251	7.97	1.12	7.1		2.15
Cesium iodide (CsI)			0.41569	102	167	1.243	8.39	1.85	4.53		1.80
Lithium fluoride (LiF)			0.46262	62.2	88.2	1.614	39.25	14.91	2.632		1.392
Sodium fluoride (NaF)			0.47632	66.9	98.3	1.69	29.87	11.68	2.558		1.336
Sodium iodide (NaI)			0.42697	94.6	151	1.305	9.49	2.59	3.67		1.775
Silica Aerogel [s]			0.52019	64	92	1.83	29.83	≈150	0.1–0.3		$1.0+0.25\rho$
NEMA G10 plate [t]				62.6	90.2	1.87	33.0	19.4	1.7		—

Spatial and Temporal Resolutions



Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10 to 150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	≥ 300 μm[b,c]	50 ns	200 ns
Drift chamber	50 to 300 μm	2 ns[d]	100 ns
Scintillator	—	150 ps	10 ns
Emulsion	1 μm	—	—
Silicon strip	$\frac{\text{pitch}}{3 \text{ to } 7}$ [e]	[f]	[f]
Silicon pixel	2 μm[g]	[f]	[f]

[a] Multiple pulsing time.

[b] 300 μm is for 1 mm pitch.

[c] Delay line cathode readout can give ±150 μm parallel to anode wire.

[d] For two chambers.

[e] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim 25$ μm) with pulse-height-weighted center finding.

[f] Limited at present by properties of the readout electronics. (Time resolution of ≤ 25 ns is planned for the ATLAS SCT.)

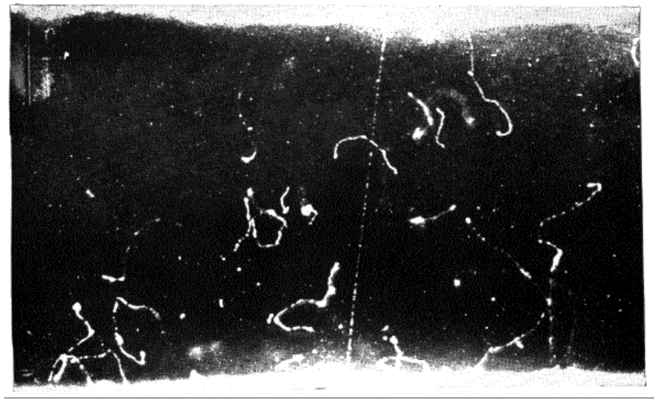
[g] Analog readout of 34 μm pitch, monolithic pixel detectors.

Pictorial Detectors

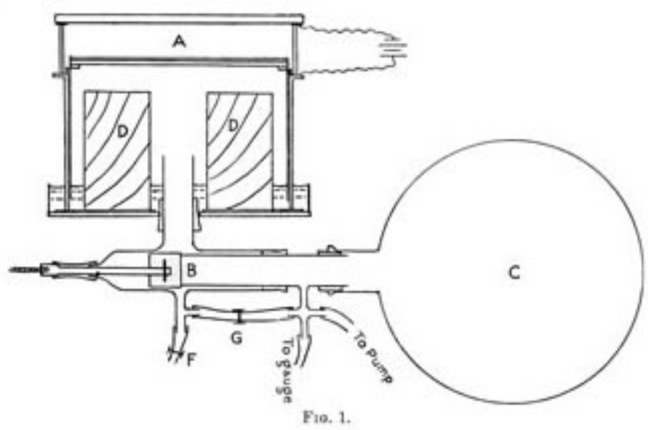
- Cloud chamber
  - condensation on track
- Emulsions
  - enhanced silver content, reveals (after development) particle tracks with extreme precision
- Streamer chambers
  - ionization of gas generates light through recombination which is photographed
- Spark chambers
  - breakdown through electrodes
- Bubble chambers
  - liquid is expanded to superheated condition

Cloud Chamber

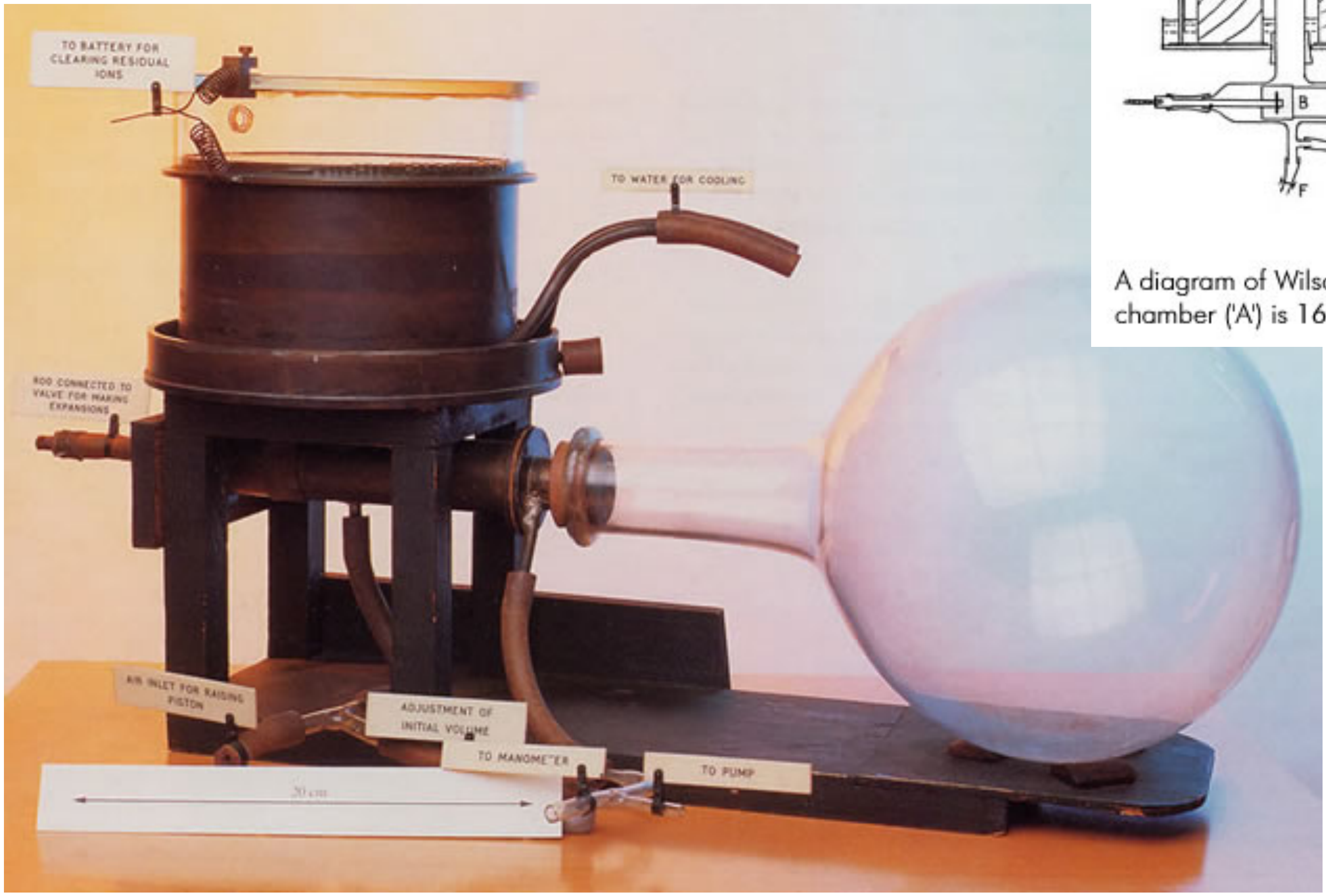
- Invented by C.T.R. Wilson for study of formation of rain in clouds
- Perfected around 1912
- expands moist air in a closed container
  - expansion cools the air
  - it becomes supersaturated
  - moisture condenses on dust particles
  - ………or paths ionized by charged particles
- Example: beta particles



Cloud Chamber



A diagram of Wilson's apparatus. The cylindrical cloud chamber ('A') is 16.5cm across by 3.4cm deep.



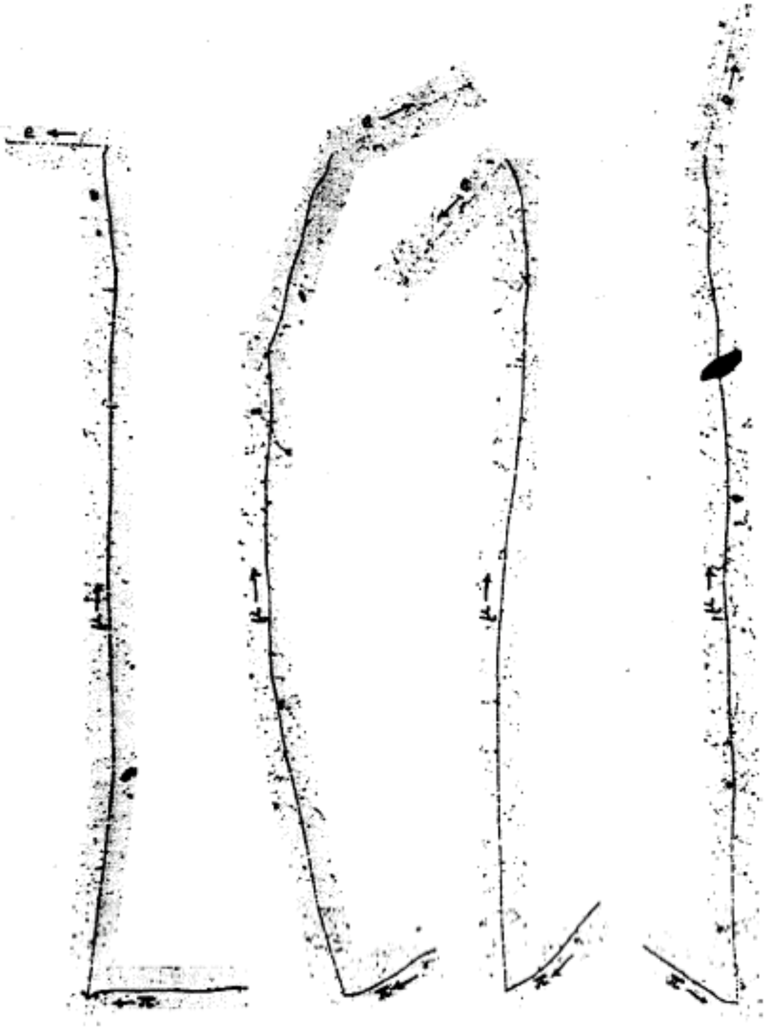
Emulsions

- Photographic film contains tiny crystals (or “grains”) of very slightly soluble silver halide salts such as silver bromide.
- The grains are embedded in gelatine which is melted and applied as a thin coating on a substrate.
- Light or radiation striking a silver halide crystals initiates a series of reactions which produce a small amount of free silver in the grain.
- Free silver produced in the exposed emulsion constitutes the “latent image,” which is later amplified by the development process.
- The free silver grains are easily reduced by “developers” to form relatively large amounts of free silver; the deposit of free silver produces a dark area on the film.
- Emulsions have superb spatial precision (~ 1 μm) but poor time precision, being continuously active.

Emulsions

- Historical example:
  - Discovery of the pion,

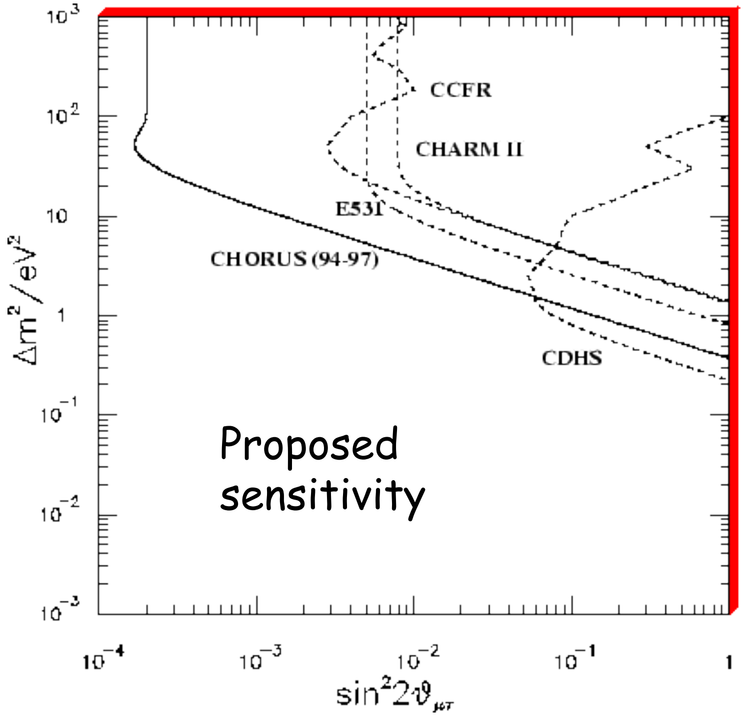
announced in 1947 by Powell et al



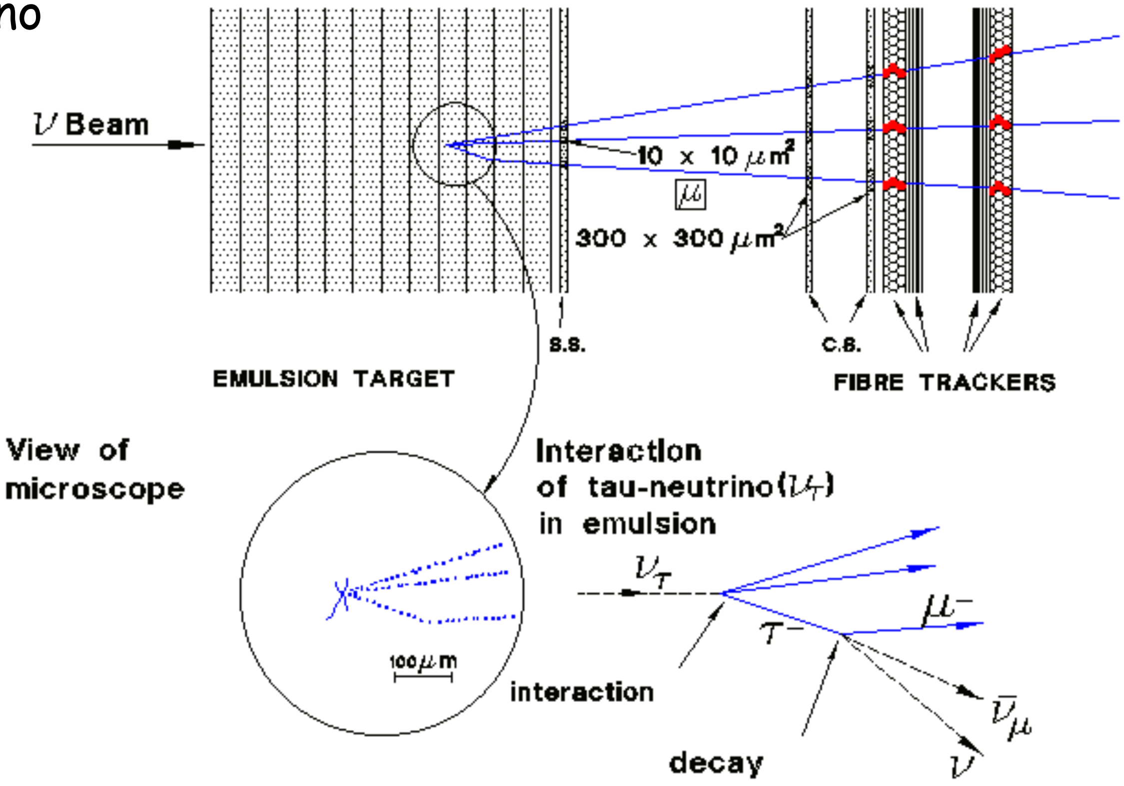
Four examples of π–μ-e decays
recorded in photographic emulsions

Emulsions

- Example:
  - Chorus experimentat CERN
  - Searched for tau-neutrino interactions



Proposed sensitivity



View of microscope

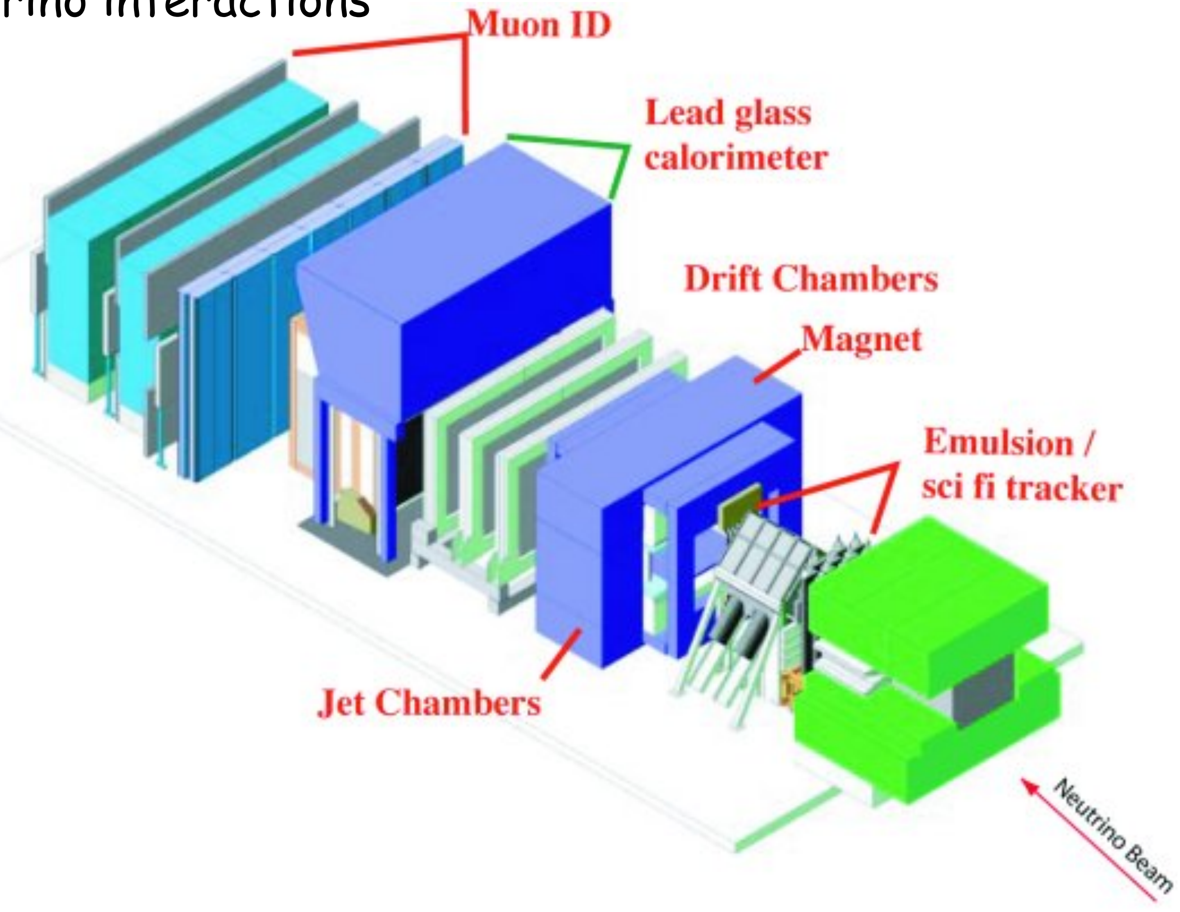
Interaction of tau-neutrino (ν_τ) in emulsion

Emulsions

- DONUT (Direct Observation of NU-Tau)
  - Discovered tau neutrino interactions
  - Search for

$$\nu_\tau + \mathrm{N} \to \tau^- + \mathrm{X}$$

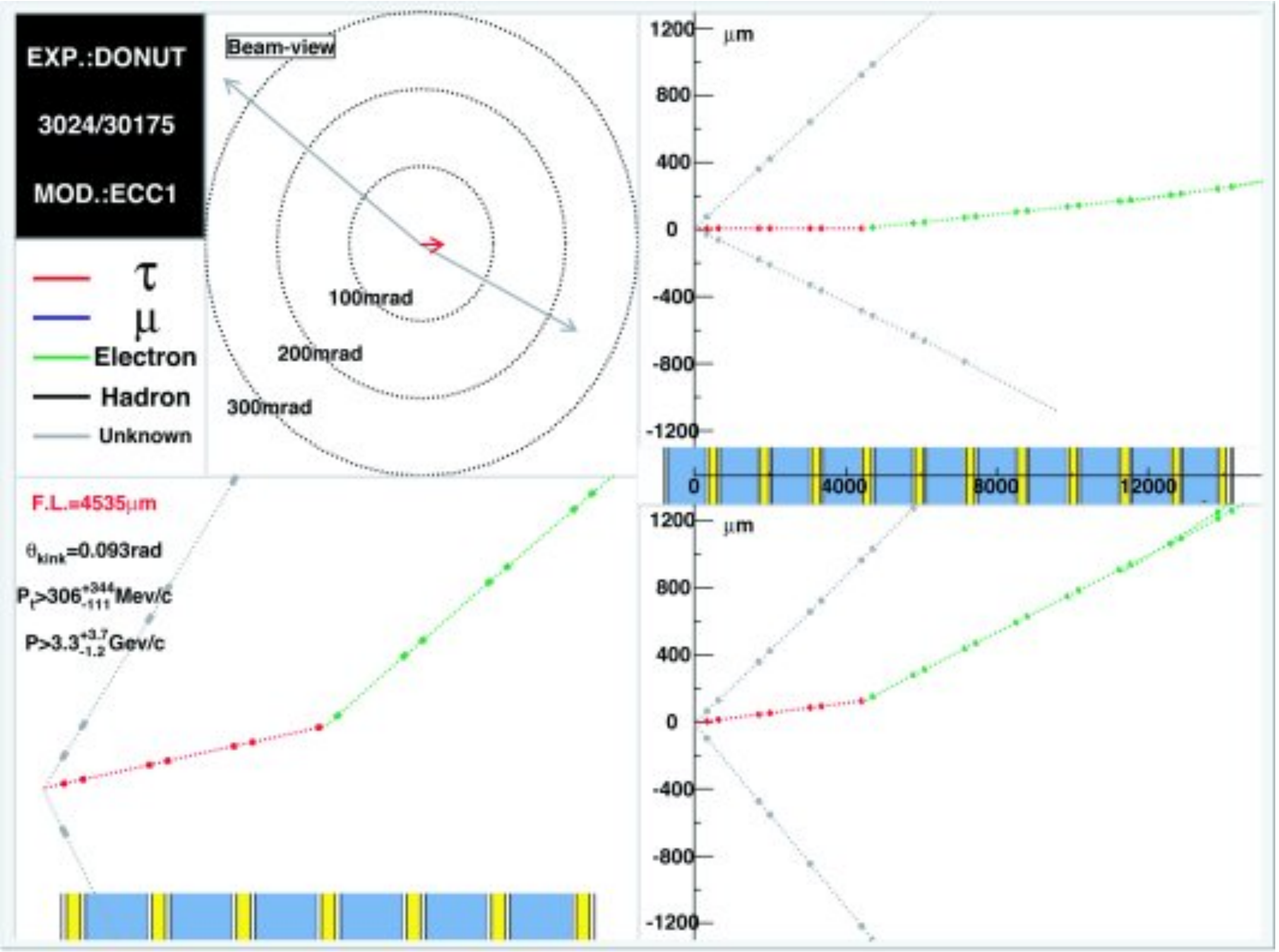
$$\tau^- \to (\mu^- \text{ or } e^-)\, \nu_\mu \nu_\tau \text{ or } \tau^- \to \mathrm{h}^- \nu_\tau$$



Emulsions

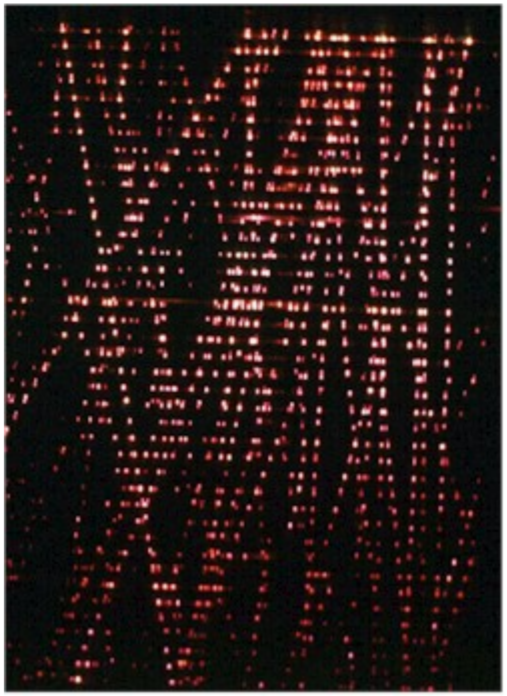
- DONUT

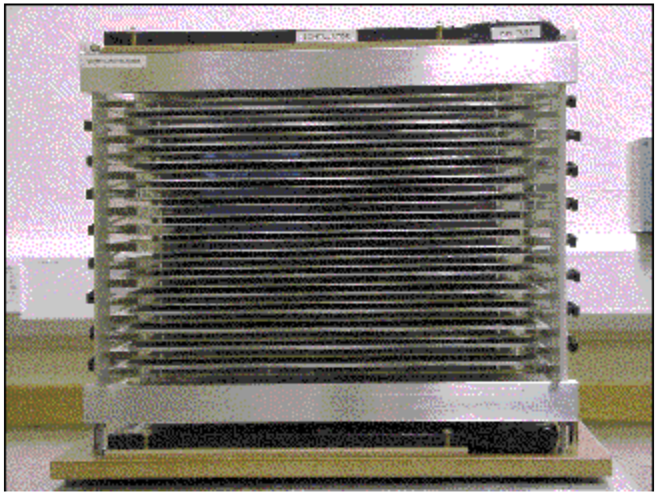
Tau neutrino interaction



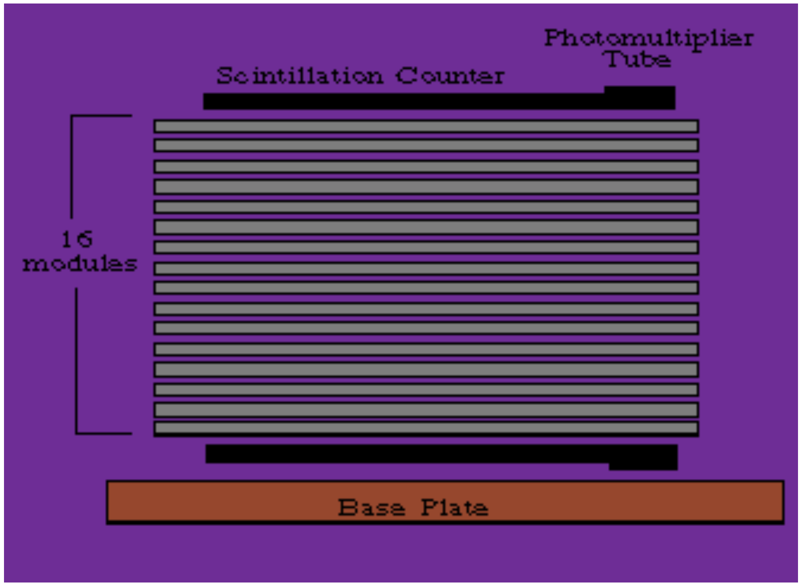
Spark Chambers

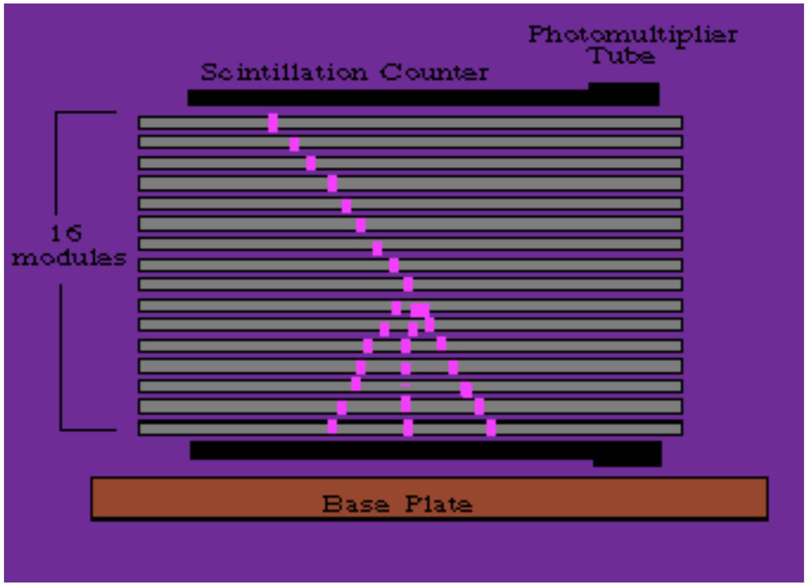
- Extremely high voltages across gaps lead to breakdown, and emission of light
- Space charge within an avalanche is strong enough to shield external field
  - recombination occurs, and emission of light
- Often multiple gaps were employed





Spark Chambers



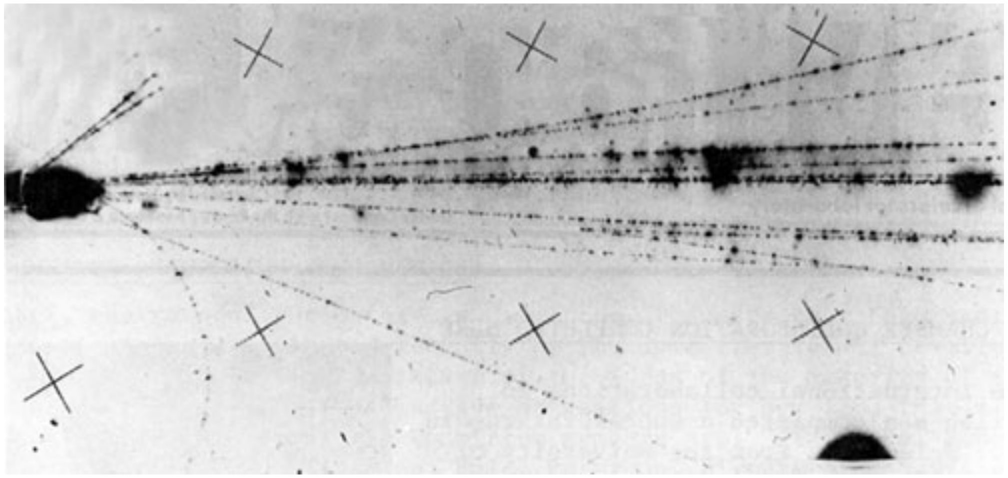


Streamer Chambers

- If a short (10 ns) high-voltage pulse (10-50kV/cm) is applied between parallel plate electrodes, a short (2-3 mm) streamer discharge develops

- Good multi-track efficiency and spatial resolution
- triggerable
- long recovery time
- processing of optical images required

- Fermilab experiment, triggered on muons, scanned for V^0s (search for charm)



Detectors

- Interaction of Charged Particles and Radiation with Matter
  - Ionization loss of charged particles ✓
  - Coulomb scattering ✓
  - Radiation loss by electrons ✓
  - Absorption of γ -rays in Matter ✓
- Detectors of Single Charged Particles
  - Proportional counters, Spark and streamer chambers, Drift chambers, Scintillation counters, Cerenkov counters, Solid-state counters,
  - Bubble chambers
- Shower Detectors and Calorimeters
  - Electromagnetic-shower detectors
  - Hadron-shower detectors

- References: Donald H. Perkins, Introduction to High Energy Physics, Fourth Edition